White Dwarf and Monaco: A Simple, Turnkey Source of <10 fs Pulses

A compact (80 cm x 80 cm x 24.4 cm) one-box source incorporating an ytterbium-fiber amplifier and a OPCPA provides turnkey access to pulse widths <9 fs with pulse energies >6 µJ and repetition rates up to 5 MHz, featuring excellent long-term (>40 hours) output stability.

Introduction

Ytterbium fiber lasers and (MOPA) amplifiers have emerged as important new sources of ultrafast pulses that can be scaled to higher average power, with simpler architecture and lower costs, than systems based on Titanium:Sapphire (Ti:Sapphire). These characteristics are proving to be key advantages in applications such as spectroscopy of solid-state materials and advanced techniques in multiphoton microscopy. Unfortunately, ytterbium cannot match the gain bandwidth of Ti:Sapphire, so these new lasers and amplifiers have typically produced longer pulse widths (100-350 fs) than those achievable from Ti:Sapphire devices. A new type of optical parametric, chirped-pulse amplifier (OPCPA) from Class 5 Photonics has removed this limitation. Incorporating a Coherent Monaco Yb-fiber amplifier and an OPCPA together in a single compact box, the White Dwarf now extends the performance of Yb-based systems into the ultrashort (<9 fs) pulse width regime while retaining all the proven advantages of Yb-fiber lasers. These include MHz repetition rates, high power, excellent output stability, and turnkey performance. This combination is ideal for applications ranging from attosecond physics to ultrafast electron diffraction and multidimensional spectroscopy. Moreover, this flexible OPCPA platform can also be implemented with longer pulse widths and tunable output from UV to NIR.

Monaco: High Power and Fast Repetition Rates

The White Dwarf OPCPA is powered by the Coherent Monaco, a next generation ultrafast amplifier based on ytterbium (Yb) fiber. Ytterbium-doped optical materials have several specific advantages as a gain medium for ultrafast lasers, making them complementary to Ti:Sapphire in scientific applications. Yb has a wide gain bandwidth, enabling mode-locked performance in the femtosecond regime, and in contrast to Ti:Sapphire, ytterbium can be directly pumped by high power laser diodes at a wavelength around 976 nm. And equally important, Yb can be doped in glass fibers.

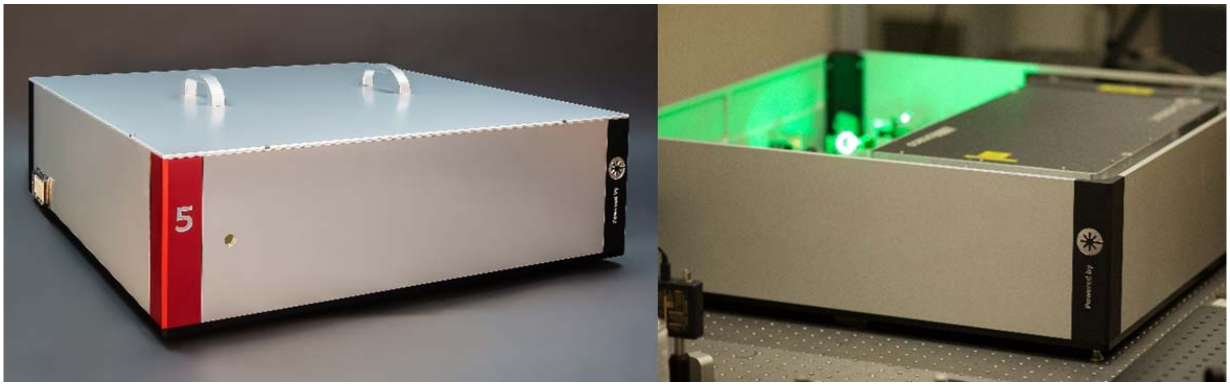

Figure 1: The White Dwarf is a self-contained OPCPA incorporating a Monaco Yb-fiber amplifier inside a single compact enclosure.

The use of fiber enables scaling to highly amplified output power because it alleviates the challenge of thermal cooling and enables simple architecture without the need to use Pockels cells as required in bulk regenerative amplifiers. Moreover, fibers can be doped and pumped in a way that allows gain saturation even at very high repetition rates, with the only caveat that non-linearities resulting from the high fluence must be addressed. So, while amplifiers using bulk gain materials are typically limited to 100s of kHz, Yb fiber amplifiers can operate up to 10s of MHz, with gain saturation delivering excellent pulse-to-pulse stability.

Reliable Yb fiber-based lasers have only become available in recent years because of several practical hurdles, mainly related to non-linear effects caused by high peak power in the gain fiber. In particular, this caused a trade-off between power and pulse width in early Yb fiber oscillators. In addition, the narrower gain bandwidth of Yb-fiber (compared to Ti:Sapphire) inherently limits the minimum achievable pulse width. In response to applications requirements, Coherent has developed high power mode-locked oscillators with 70-150 fs pulse widths, and higher energy, amplified systems with 250-350 fs pulse durations.

The Coherent Monaco is one of these Yb-fiber based amplifiers using a master oscillator/power amplifier (MOPA) configuration to deliver high power and high stability output at a fixed 1035 nm wavelength. Because of the inherent simplicity and stability provided by its fiber architecture, Monaco is a sealed one-box industrial-grade laser featuring a compact footprint and turnkey on-demand performance. Key specifications of the Monaco are pulse energy of 80 μJ, repetition rates from single shot to 50 MHz, pulse width < 350 fs, pulse-to-pulse stability < 1.5% RMS, and a circular beam profile with M2 < 1.2. This superior stability and output beam quality make it ideal for pumping optical parametric devices such as a tunable optical parametric amplifier (OPA), like the Coherent Opera, or an optical parametric chirped-pulse amplifier (OPCPA), such as the White Dwarf OPCPA described here, that provides extremely short pulse widths.

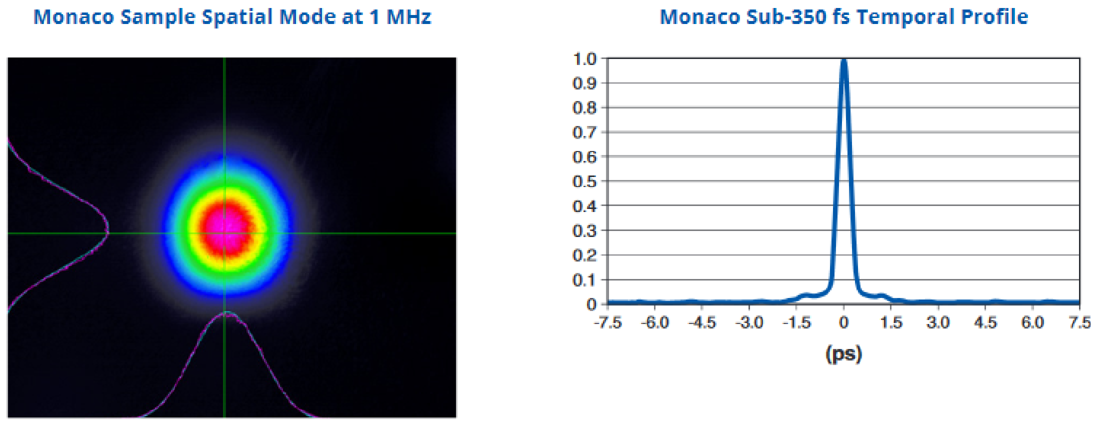

Figure 2: The Monaco is a Yb-fiber MOPA with a circular TEM00 output beam and a pulse width < 350 fs.

White Dwarf – A Proven OPCPA Approach

The White Dwarf OPCPA is a femtosecond OPCPA seeded by white light generation (WLG) utilizing a ruggedized and compact architecture, designed to operate at repetition rates up to 5 MHz. OPCPAs were originally developed to enable amplification of a short pulse width seed laser with a long pulse width pump source without compromising the seed's transform limited pulse width. But in the White Dwarf, the Monaco supplies both the seed (signal) and the pump pulses to drive the OPCPA. This simplifies synchronization between the two pulse paths by an intrinsic and passive timing stability, avoiding the need for a complex timing feedback device. Additionally, it avoids the cost and complexity of using a separate pump source.

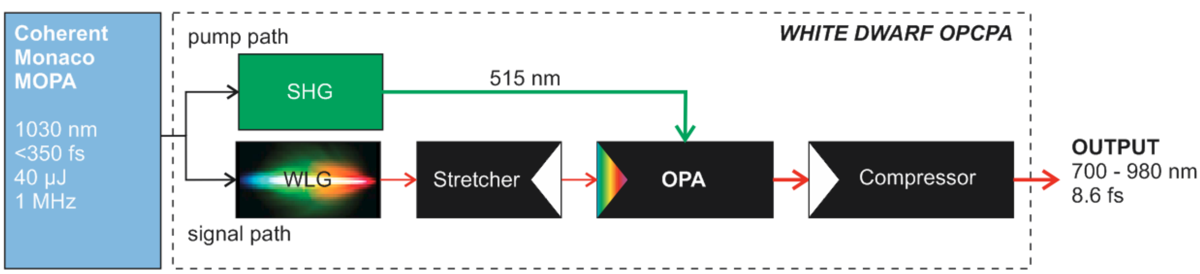

Figure 3: The Main components of the White Dwarf.

The key elements of the White Dwarf OPCPA are shown schematically in figure 3. The Monaco output pulses are split into a pump path and a signal path via a beamsplitter. The seed path uses a small portion (< 8%) of the output power to generate a broadband signal in a bulk dielectric crystal (WLG crystal) by a well-known filamentation and self-focusing mechanism. By optimizing the beam diameter and crystal length, this white light generation (WLG) process is entirely coherent; all the various wavelength components of the white light pulse have the same phase-locked characteristics as the input pulse from the Monaco. However, the bandwidth of the pulse is now greatly extended far beyond the bandwidth of ytterbium – see figure 4. The pulse width of this WLG output pulse is thus only a few femtoseconds, as determined by the natural dispersion of the WLG crystal.

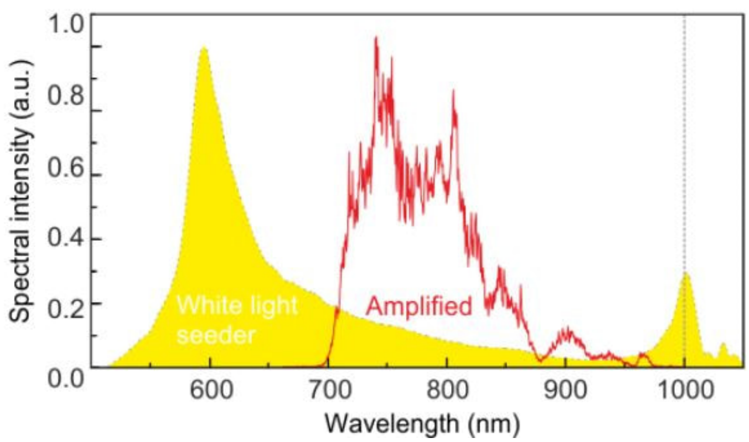

Figure 4: The spectral profile of the WLG output and the amplified output from the OPA stage.

In order to fully utilize the energy of the 350 fs pulses from the Monaco, the white light pulse is stretched (chirped) using the natural dispersion in a piece of optical glass. The chirped signal pulses are then focused into a single-stage optical parametric amplifier (OPA) with broadband non-collinear phase-matching. The OPA consists of a beta-barium borate (BBO) crystal with pump pulses provided by frequency doubling of the 92% portion of the Monaco output at a wavelength of 515 nm.

Finally, the amplified signal pulses are temporally compressed using broadband chirped-mirrors with >99.9% reflection.

Short Pulse widths or Tunable Output

Using Monaco for both the seed and pump pulses simplifies the challenge of temporally overlapping them in the OPA crystal and eliminates any timing jitter[1]. And by incorporating an optical delay line in the pump optical path, this relative timing can be optimized in several ways. To obtain the shortest pulse width output, the pump pulse is timed to overlap a broad portion of the chirped seed pulse spanning 700-980 nm. This wide bandwidth results in an output pulse of just a few optical cycles. The actual pulse width has been characterized using a scanning intensity autocorrelator with a 10 µm thick BBO. The autocorrelator trace is shown in figure 5, revealing 8.6 fs FWHM, assuming a Gaussian pulse. In this mode of operation, the compressed output pulse energy is >3 µJ at a repetition rate of 1 MHz.

Alternatively, the stretcher and delay line can be tuned by the user so that the pump pulse only overlaps with a small spectral slice of the seed pulse. This provides a simple route to tunable output. Here, the longest pulse duration is approximately 300 fs, as determined by the Monaco.

[1] It is important to understand that the purpose of the seed pulse stretching is to overlap the seed and pump pulses in space and time within the OPA crystal. It is not to limit thermal loading or peak power damage as in amplified Ti:Sapphire systems. Indeed, the OPA mechanism does not develop stored gain as in a regenerative amplifier. This results in minimal absorbed power in the BBO crystal which therefore does not require active cooling, minimizing system complexity and cost.

With this pulse width, the output bandwidth is approximately 3 nm (FWHM). Due to the single-pass high gain nature of the OPCPA, tuning can be achieved without significant losses in the output energy or changes in the output pulse duration, making this OPCPA an ideal system for experiments where tunable sources are required.

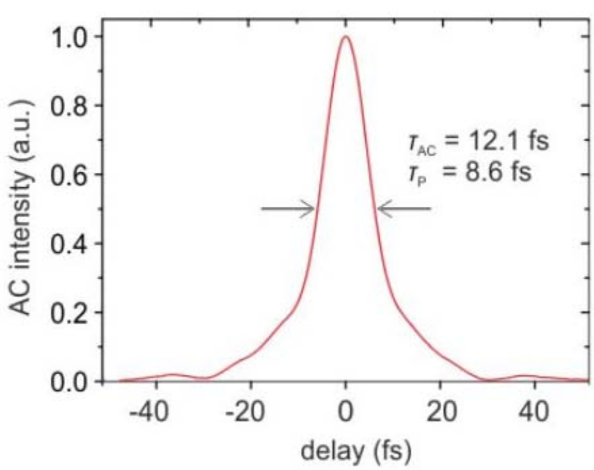

Figure 5: Autocorrelator measurements show that the White Dwarf output pulse width is 8.6 fs.

Excellent Beam Quality and Output Stability

The long term power stability of the White Dwarf OPCPA has been measured over 40 hours of operation and confirmed to be <0.5% rms, as shown in figure 6. The measured pulse-to-pulse energy stability is better than ±2% due to the absence of seed-pump timing jitter and the low-noise WLG stage.

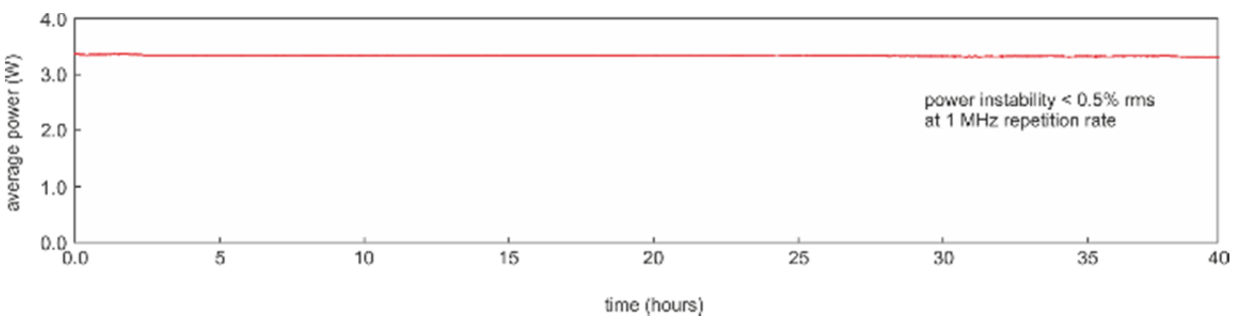

Figure 6: Long term power stability of the White Dwarf operating at a pulse width of 8.6 fs and a 1 MHz repetition rate.

Early WLG systems tended to be noisy with limited stability. But the next generation WLG in the White Dwarf OPCPA has been optimized to deliver unprecedented long-term stability and pulse-to-pulse stability. This has been experimentally confirmed via two studies. The pulse-to-pulse WLG stability was measured using a fast photodiode (Thorlabs DET10A) and a 4 GHz oscilloscope (LeCroy), evaluating 1000 consecutive pulses. With 1.9% rms input fluctuations from the Monaco, the measured fluctuations in the WLG output were only 1.2% rms. This improvement of the pulse-to-pulse stability is due to an intensity clamping effect at the optimum operation point of the WLG. In addition, the long-term stability of the WLG stage was measured over a 28 hour period with an earlier ultrafast input source that predated Monaco. The published results (Riedel et al., Opt. Exp. 21, 28987, 2013) showed a similar increase in stability: <0.85% rms WLG output with <0.65% rms input.

The circular beam quality of the White Dwarf OPCPA pumped by Coherent Monaco is excellent and close to diffraction limited. For determining the M² value, the output beam was focused by an achromatic lens. The beam profile was then recorded along the propagation axis with a beam profiler (WinCam D). The beam caustic was then fitted to the second moment values of the beam profiles indicating M² < 1.2 for both axis – see figure 7.

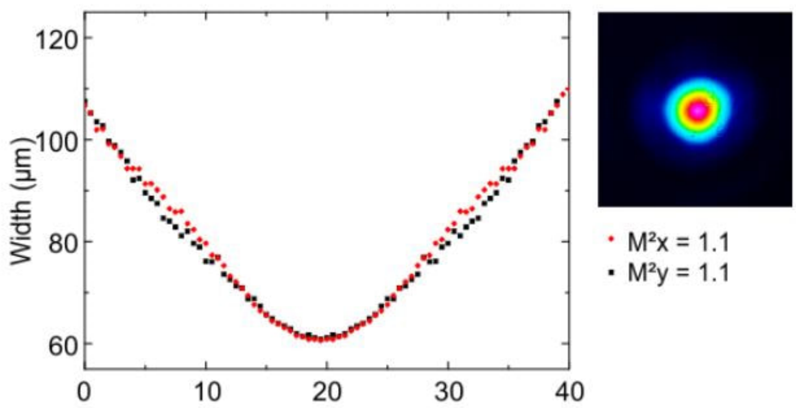

Figure 7: The output is characterized by M2 values < 1.2 in both axes.

Infrared capabilities

The White Dwarf OPCPA and Monaco combination also allows the direct amplification of near-infrared wavelengths between 1350 and 1650 nm. In this White Dwarf-IR configuration, the system uses a KTA nonlinear crystal, pumped directly at 1030 nm by the Monaco fundamental, instead of its SHG at 515 nm. The key output and performance parameters, such as the high long-term stability, the excellent beam profile, the high conversion efficiency and the option of tunable operation, are all similar to the 700-980 nm version. The typical achievable pulse duration is < 50 fs.

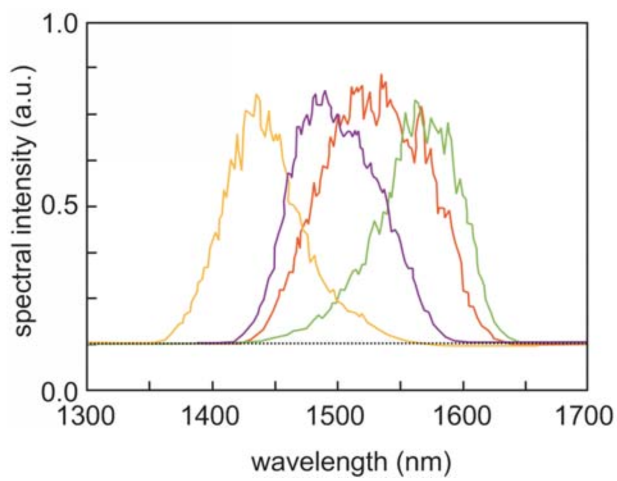

Figure 8: Infrared output spectrum and tunability of the White Dwarf IR OPCPA

Summary of White Dwarf Advantages

There are several key advantages for the Monaco-powered White Dwarf OPCPA as a source of amplified ultrafast pulses.

- Simple turnkey access to extremely short (<9 fs) pulses.
- The high repetition rate is ideal for applications with low S/N and/or large data sets.
- It can be configured for broad wavelength tuning.
- The high single pass gain enables high power in a compact platform.
- Low absorption in the OPA eliminates the need for aggressive cooling.
- This low thermal load eliminates warm-up, providing performance on demand (warm-up times are less than 5 minutes).

Summary

The development of Yb-fiber based oscillators and amplifiers is revolutionizing ultrafast science, providing simplified access to output parameters that were not possible with Ti:Sapphire systems, namely high repetition rates with high average power. Now the combination of a Yb amplifier and a novel OPCPA extend this turnkey simplicity to the ultrashort pulse width regime, delivering <9 fs pulse widths at microjoule pulse levels and MHz repetition rates.

Standard Products

Class 5 Photonics offers the following standard White Dwarf OPCPA systems with integrated Coherent Monaco fiber laser.

Parameter (Max.)	WD-40	WD IR-40	WD-40-960	WD-40-1300
Central wavelength	**700 - 950 nm**	**1400 - 1700 nm**	**960 nm**	**1300 nm**
Average power	3 W	3 W	3 W	3 W
Pulse energy	up to 6 μJ			
Repetition rate	up to 5 MHz			
Pulse duration	<10 fs	<40 fs	<100 fs	<100 fs